



Yield and gas exchange of greenhouse tomato at different nitrogen levels under aerated irrigation

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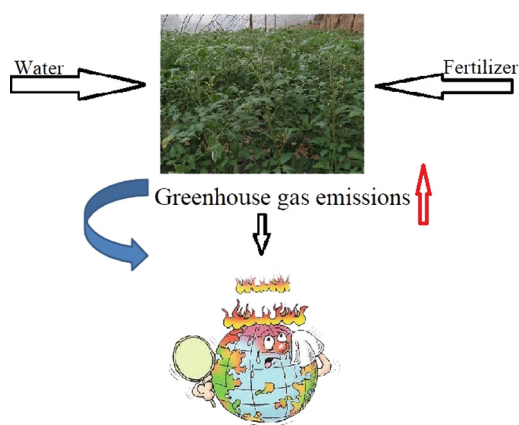
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HIGHLIGHTS

- AI along with N application significantly increased crop yield, but also increased the GHG emissions.
- Tomato yield, soil CO₂ and N₂O emissions in Spring cultivation were 5.1%, 10.6% and 43.8% higher than Autumn cultivation.
- The Autumn season along with AI and 200 kg N ha⁻¹, was recommended to avoid adverse effects of a warming environment.
- AI and 150 kg N ha⁻¹ in Spring cultivation could be recommended as an alternative measure.

GRAPHICAL ABSTRACT



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ABSTRACT

Significant global warming increases over the last century have resulted in recent research focused on practices to reduce greenhouse gas (GHG) emissions. Agricultural management practices, such as nitrogen (N) fertilization and aerated irrigation (AI), have significantly increased crop yields by improving soil water and fertilizer availability, and have been widely adopted in recent years. However, the interactive impact of different growing seasons and management practices in the greenhouse on GHG emissions is unclear. This greenhouse study was conducted during Spring and Autumn cultivation periods in Yangling, China with five N application rates (0, 50, 150, 200, 250 kg ha⁻¹) and two irrigation methods (AI and conventional irrigation [CK]). The results indicated that AI and N application both increased tomato yield, but also increased soil CO₂ and N₂O emissions. The temperature was 4 °C higher during Spring cultivation than during Autumn cultivation, which significantly ($P < 0.05$) increased soil emissions of CO₂, N₂O, and net GHG by 10.6%, 43.8%, and 12.3%, respectively. However, the yield in Spring cultivation only increased by 5.1% ($P > 0.05$). Thus, among the selectable cultivation seasons, the cooler season (Autumn) along with AI and 200 kg N ha⁻¹, was recommended to farmers to avoid adverse effects of a warming environment. AI and 150 kg N ha⁻¹ in Spring cultivation could be recommended as an alternative measure to local farmers. Our results suggest that in a future warmer climate, reducing nitrogen fertilizer

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rate in conjunction with the use of AI will remain important practices for maintaining crop yield while reducing soil net GHG emissions. There is an urgent need to transform current management practices to offset the negative impacts of climate change.

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1. Introduction

Anthropogenic emissions of CO₂ as well as other greenhouse gases (GHGs) have changed the global climate, causing increased temperatures worldwide (Guo and Zhou, 2007). China's Ministry of Science and Technology officially released China's "Third National Assessment Report on Climate Change" in 2015 (The Editorial Board of Third National Assessment of Report on Climate Change of China, 2015), which reported that average temperatures across China have risen by 0.9 to 1.5 °C from 1909 to 2011. This trend is expected to intensify in the future and temperatures across most of China will likely rise another 1.3 to 5.0 °C by the end of this century. The global warming trend is predicted to accelerate with greater warming in agroecosystems. According to the IPCC (2007), global agriculture is responsible for 10–12% of the anthropogenic greenhouse effect, releasing 5.1–6.1 Pg CO₂-equivalent (CO₂-eq) of GHGs to the atmosphere. It is challenging to mitigate GHG emissions from cultivated soils. In greenhouse cultivation, to acquire higher crop yield, water and fertilizer are intensively managed, which promotes GHG emissions and subsequent global warming (He et al., 2006; Zhao et al., 2010). Changing agricultural practices such as irrigation and N application may be a viable method to increase soil organic matter content and thereby decrease CO₂ and N₂O emissions (Trost et al., 2013; Liu et al., 2015; Lu et al., 2011).

N is the most required nutrient for plants and it plays a crucial role in crop yield formation by establishing and maintaining photosynthetic capacity and sink capacity (Below, 2001). Additional N fertilizer is typically needed for crops to achieve optimum yields. However, N₂O emissions increase with increased N fertilization rates (Bouwman et al., 2002; Halvorson et al., 2008) and when N availability exceeds plant demand (Chantigny et al., 1998). Sun and Huang (2012) indicated that N fertilizers alone account for about 60% of the global anthropogenic emissions of N₂O. In addition, N application may increase or decrease CO₂ emissions by influencing the soil organic carbon (SOC) contents (Campbell et al., 2000; Recous et al., 1995). In a meta-analysis, N application was found to increase the SOC storage in agricultural soils by 3.48%, i.e. it decreased CO₂ emissions (Lu et al., 2011). Zamanian et al. (2018) reported that N fertilizer raised soil CO₂ emissions from inorganic carbon resulting from soil acidification in carbonate-containing soils. By increasing yields, N fertilizer affects GHG emissions.

Irrigation is another relevant production factor that affects yield-related GHG emissions (Trost et al., 2013). Aerated irrigation (AI) in particular is an irrigation strategy proposed to increase crop yield and water use efficiency (Bhattarai et al., 2006; Du et al., 2018a). AI transports aerated water to the root zone, which has the potential to ameliorate hypoxic or anoxic conditions and promote plant water and nutrient uptake. Undoubtedly, changes in soil oxygen content affect soil nitrification, denitrification, and subsequent N₂O emissions (Khalil et al., 2004). AI has been widely used in agricultural system in recent years, e.g. tomato, pepper, orchards, zucchini, soybean, and cotton (Friedman and Naftaliev, 2012; Bhattarai et al., 2004; Goorahoo et al., 2002; Hou et al., 2016). However, the response of soil GHG emissions and yield to AI along with N application has not been quantified.

In addition to management practices, Wang et al. (2018) also reported that temperature was one of the key environmental factors affecting crop yield and soil CO₂ and N₂O emissions. Previous studies in forest (Zou et al., 2018; Savage et al., 2013), grassland (Zou et al., 2018; Graham et al., 2014), and meadow (Peng et al., 2014; Chen et al., 2017) environments showed that increasing soil temperature significantly promoted soil CO₂ and N₂O emissions. Li et al. (2019)

reported that soil warming decreased wheat yield and N₂O emissions and increased soil CO₂ emissions, but irrigation reduced these negative effects. Some studies have indicated that the interaction of warming and N fertilization had no significant effects on soil CO₂ (Liu et al., 2015), but increased N₂O emissions by 26.2% (Chen et al., 2017). These results show that it is necessary to take temperature into account in assessing crop yield and GHG emissions. Furthermore, temperature variations in greenhouses among different growing seasons were very large. However, information on the interactive impact of climate differences between different growing seasons and management practices on yield and GHG emissions under greenhouse cultivation is limited.

Tomato is the main vegetable crop grown in solar greenhouses in northwestern China due to its high potential yield and profitability (Du et al., 2017; Hou et al., 2016). To obtain a better understanding of how management measures interact with temperature to affect crop yield and GHG emissions, tomato production in two typical growing seasons (Spring and Autumn) was investigated in the present study. We hypothesized that AI in combination with N fertilization would increase tomato yield and net GHG emissions and higher temperature seasons would intensify this effect. Facing a warming climate, adopting AI along with reduced N application in greenhouse cultivation could offset the negative effects of higher temperature.

2. Materials and methods

2.1. Experimental site

The study site was located in Yangling, Shaanxi province (northwestern part of China) at 34°17' N, 108°02' E, 521 m above mean sea level. The climate of the study area was characterized as a sub-humid area prone to drought. The average annual precipitation is 632 mm, along with annual sunshine hours of 2164 h, temperature of 12.9 °C, and a frost-free period of >210 d. The volumetric water contents at field capacity and dry bulk densities were 0.24 m³ m⁻³ and 1.27 g cm⁻³, 0.23 m³ m⁻³ and 1.45 g cm⁻³, and 0.24 m³ m⁻³ and 1.42 g cm⁻³ in 0–20, 20–40, and 40–60 cm layers, respectively. The organic-matter, total N, phosphorus (P), and potassium (K) contents in the 0–20 cm soil layer before transplantation were 15.94, 1.66, 0.39, and 1.82 g kg⁻¹, respectively. The air temperature and solar radiation measurements were collected with an automatic weather station (HOBO ware, Onset, Massachusetts, USA) located in our greenhouse.

2.2. Experimental design

The experiment was conducted in the solar greenhouse. The greenhouse was 110 m long × 9 m wide with a planting area of 605 m², covered with a 0.2 mm thick thermal polyethylene sheet. And the greenhouse was east-west orientation and passively ventilated by roof vents (Fig. 1). The greenhouse is widely used by farmers, and no any warming facility in it. Tomato seedlings were transplanted in a greenhouse for Spring cultivation on 29 March and harvested on 7 July in 2017. Tomato seedlings for Autumn cultivation were transplanted on 8 August 2017 and harvested on 8 January 2018. The experiment had five N application treatments (0, 50, 150, 200 and 250 kg ha⁻¹) and two irrigation treatments (AI and CK). Each experimental plot was 5.5 m × 3.5 m. Each treatment combination was replicated three times. The plant row spacing was 50 cm with 45 cm between each plant in a row.

Fertilizer N, P, and K sources used in the present study were urea (N = 46% by weight), biological phosphorus (P₂O₅, P = 16% by weight), and

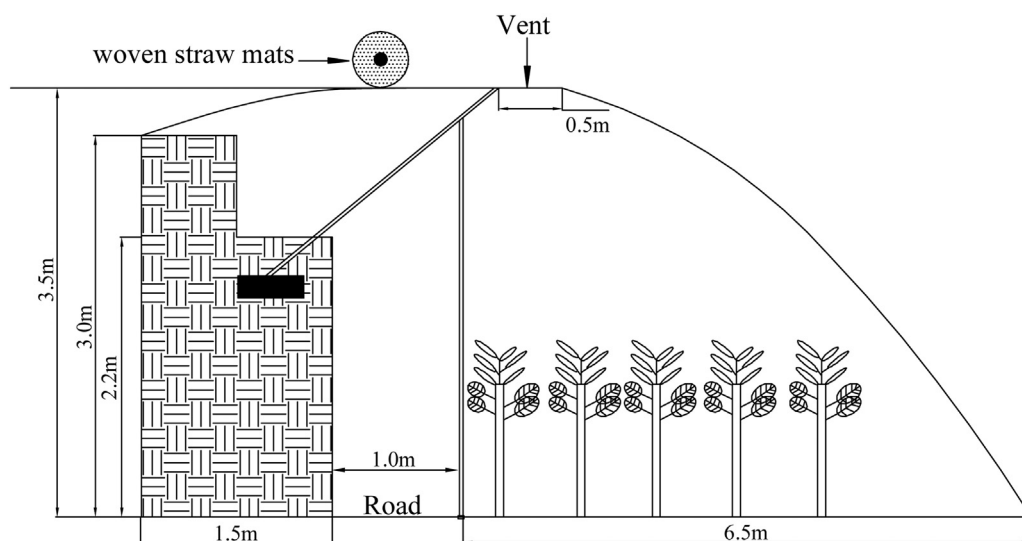


Fig. 1. A sectional diagram of solar greenhouse in northwest China. The shaded section of 1.5 m width and the stippled area are the back insulated wall and rear slope which are often built with soil and slag, respectively, for maintaining the interior temperature.

calcium super-phosphate (K_2O , $K = 51\%$ by weight), respectively. Fertilizers were applied at rates of $150 \text{ kg P}_2\text{O}_5 \text{ ha}^{-1}$ and $200 \text{ kg K}_2\text{O ha}^{-1}$ in both seasons. Irrigations were applied through drip irrigation tape buried 15 cm below the soil surface with dripper spacing of 35 cm. A flow meter and control valve were installed in each plot to measure and control the water and air volume. Irrigations were applied at seven-day intervals and the amount applied corresponded to the cumulative evaporation from a 20 mm diameter evaporation pan since the previous irrigation. Air injection into the irrigation water was accomplished by mixing air using a Mazzei air injector model 684 (Mazzei Injector Company, Bakersfield, California, USA), which was installed in-line immediately following the water source. The injector valve was opened when conducting AI and the system sucked air (bubbles) into the irrigation water entering the drip lines (Goorahoo et al., 2002; Bhattarai et al., 2006). However, the injector valve was closed for CK.

2.3. Gas flux measurements and net GHG emissions

Soil gas samples were collected every seven days beginning 10 days after transplanting during both seasons. The static chamber in situ method was used to measure GHG (Hou et al., 2016). A stainless-steel frame ($30 \times 30 \times 3 \text{ cm}$) with a groove on the top surface was inserted into the soil at a position 20 cm between tomato plants and remained in place during the entire growing season. During the measuring period, a chamber ($30 \times 30 \times 50 \text{ cm}$) was inserted onto the water-filled groove of the frame previously inserted into the soil, thereby providing an airtight seal for the top chamber which remained in place for 30 min. Air samples were taken with 50 ml plastic syringes by way of a three-way stopcock at 0, 10, 20, and 30 min after chamber closure. Measurements were conducted between 9:00 am and 11:00 am. The concentrations of the collected gas samples were subsequently analyzed with a gas chromatograph (Agilent 7890A, Agilent Technologies, Inc., Santa Clara, America) equipped with a flame ionization detector and an electron capture detector for measuring CO_2 and N_2O , respectively. The soil CO_2 and N_2O emissions were calculated by the following equation (Rolston, 1986):

$$F = \rho \cdot h \cdot \frac{273}{273 + T} \cdot \frac{dc}{dt} \quad (1)$$

where F is the gas emission flux ($\text{mg m}^{-2} \text{ h}^{-1}$ for CO_2 , $\text{ug m}^{-2} \text{ h}^{-1}$ for N_2O); ρ is the gas density at the standard state (g cm^{-3}); h is the height of the chamber (m); T is the air temperature inside the chamber during

the sampling ($^{\circ}\text{C}$); dc/dt is the rate of CO_2 and N_2O gas accumulation in the chamber.

Seasonal cumulative emissions of CO_2 and N_2O during both growing seasons were calculated by the following equation (Singh et al., 1999):

$$E_{\text{N}_2\text{O}} \text{ or } E_{\text{CO}_2} = \sum [(F_{i+1} + F_i)/2] \times (D_{i+1} - D_i) \times 24/1000 \quad (2)$$

where F is the soil CO_2 or N_2O flux, $\text{mg m}^{-2} \text{ h}^{-1}$ or $\text{ug m}^{-2} \text{ h}^{-1}$; i is the i th measurement; $D_{i+1} - D_i$ is the number of days between two gas sampling dates.

Based on these cumulative emission results, annual net GHG emission was calculated as the sum of annual soil CO_2 and N_2O emissions in CO_2 -equivalents ($\text{CO}_2\text{-eq}$). On a 100-year time horizon, global warming potential of N_2O is 298, and CO_2 is 1 (IPCC, 2013). Positive and negative values of net GHG represent the soil as a source and sink of atmospheric CO_2 and N_2O emissions, respectively.

2.4. Soil sampling and crop yield

Soil temperature, moisture, and soil oxygen content were measured at the same time that GHG emissions were measured. We measured soil temperature using geothermometers (HongXing Instruments Factory, Wu Qiang Country, Hebei Province, China) at a soil depth of 10 cm and gravimetric soil water content at a soil depth of 20 cm (soil samples were oven-dried at 105°C). The soil oxygen content was measured using the Pyro oxygen logger (Firesting O_2 , Pyroscience, Germany). The soil water-filled pore space (WFPS, %), defined as the ratio of soil pore to total soil volume, was calculated by the following equation (Beare et al., 2009):

$$\text{WFPS} = \frac{W}{1 - r/2.65} \times r \times 100 \quad (3)$$

where W is the soil gravimetric water content, %; r is the soil bulk density, assumed to be 1.35 g cm^{-3} .

At fruit maturity, 14 plants in the middle of each plot were manually harvested. The number of fruits for each plant and the single fruit weights were recorded at harvest time in both seasons.

2.5. Statistical analysis

Data analysis was conducted using SPSS 18.0 software. Treatment effects were assessed using the one-way analysis of variance, and the

differences between treatments were determined using the least significant difference test (LSD) at the 0.05 significance level. Correlation analyses were performed to investigate the relationship between soil GHG and soil variables. The figures were generated using Origin 8.0 data analysis and graphing software and R 3.4.3 software.

3. Results

3.1. Seasonal variation of environmental variables

The daily solar radiation at the study site ranged from 7.3 to 195.4 MJ m⁻² d⁻¹ and 0.6 to 151.0 MJ m⁻² d⁻¹ during the Spring cultivation period and the Autumn cultivation period, respectively. The mean seasonal solar radiation during Spring cultivation was about two times greater than that during Autumn cultivation (Fig. 2a and f). This seasonal pattern is similar to the 10-year average (2008–2017) at the Yangling weather station (data not shown).

Daily average air temperatures generally increased over time during Spring cultivation and ranged from 13.3 to 31.1 °C. In contrast, the daily average air temperatures during Autumn cultivation decreased with time over the growing season, ranging from 24.8 to 6.9 °C. Mean seasonal air temperature during Spring cultivation was 7.5 °C higher than that during Autumn cultivation (Fig. 2b and g).

Seasonal variation of soil temperature in the top 10-cm layer was similar to that observed for air temperature, ranging from 17.2 to 28.0 °C during Spring cultivation and from 11.0 to 26.5 °C during Autumn cultivation (Fig. 2c and h). Mean seasonal soil temperature during Spring cultivation

was 4 °C higher than during Autumn cultivation. Higher temperatures during Spring promoted higher evaporation than during Autumn and thus decreased soil mean WFPS by 3.8% (Table 1). In addition, soil WFPS generally decreased with increasing N application. Under the same N application rate, soil WFPS in AI treatment was generally lower than in CK treatment. However, because of the high frequency of irrigation in the greenhouse, the soil water content was always maintained at a high level (Fig. 2d and i). In contrast, the higher soil water content tended to decrease the soil oxygen concentration during the growing season (Fig. 2e and j).

3.2. Soil CO₂ fluxes

Soil CO₂ fluxes exhibited the same distinct seasonal trends as soil temperature for both Spring cultivation and Autumn cultivation (Fig. 3a and b), with values ranging from 62.2 to 328.3 mg m⁻² h⁻¹ and from 33.2 to 302.9 mg m⁻² h⁻¹ in the Spring cultivation and Autumn cultivation periods, respectively. Averaged across the Spring cultivation period, the mean soil CO₂ flux was 196.5 mg m⁻² h⁻¹, which was 43.1% higher than the flux in the Autumn cultivation period. Furthermore, during the warmer Spring cultivation period, the cumulative total soil CO₂ emission was 4.40 Mg C ha⁻¹, which was 10.6% (*P* < 0.05) greater than during the Autumn cultivation period (Table 1).

Soil CO₂ emissions increased with increasing N application rate up to 200 kg N ha⁻¹, after which CO₂ emissions decreased. This pattern was seen in both Spring and Autumn cultivation periods, but emission values were higher during the warmer Spring period. (Fig. 4b; Fig. 5c).

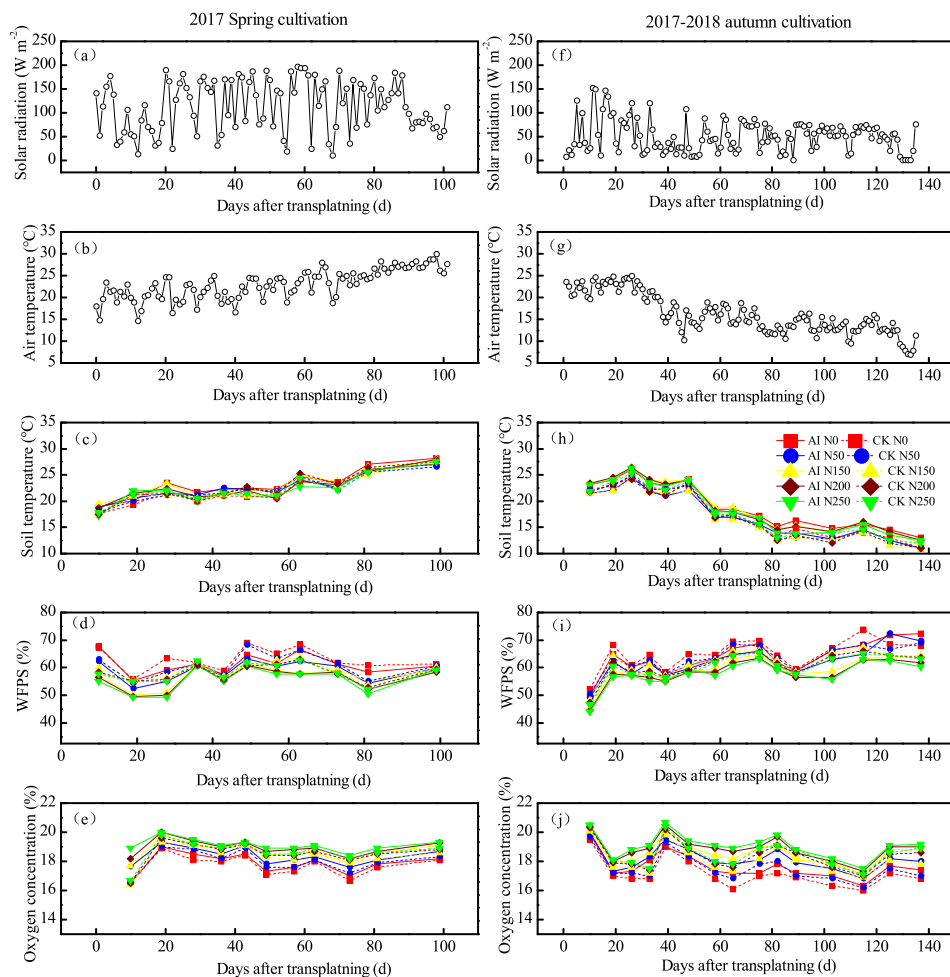


Fig. 2. Seasonal variation of (a) solar radiation (b) air temperature (c) soil temperature (d) soil water-filled pore space (WFPS) (e) soil oxygen concentration during spring tomato cultivation in 2017 and corresponding values of these variables, (f), (g), (h), (i) and (j), during autumn cultivation in 2017–2018 at Yangling, China.

Table 1

Mean soil temperature, soil water-filled pore space (WFPS), cumulative soil N₂O emissions, and cumulative soil CO₂ emissions during the Spring and Autumn tomato cultivation periods at Yangling, China.

Treatments			Soil temperature (°C)	Soil WFPS (%)	Cumulative N ₂ O emissions (Mg C ha ⁻¹)	Cumulative CO ₂ emissions (Mg C ha-1)
Spring	I	AI	22.7 a	57.8 a	0.33 a	4.43 c
		CK	22.3 a	59.9 b	0.32 a	4.37 c
	N	N0	22.6 b	62.2 a	0.05 e	3.61 a
		N50	22.4 b	59.9 b	0.13 d	4.35 b
		N150	22.6 b	58.0 b	0.34 c	4.75 d
		N200	22.5 b	57.2 b	0.51 b	4.94 e
		N250	22.2 b	57.0 b	0.57 a	4.5 c
Mean		22.50	58.90	0.32	4.40	
Autumn	I	AI	19.1 b	60.2 a	0.23 a	4.0 d
		CK	17.9 bc	62.2 b	0.22 ab	3.96 d
	N	N0	18.9 a	64.3 a	−0.04	3.35 a
		N50	17.9 a	62.6 b	0.11 h	3.97 b
		N150	18.5 a	60.6 c	0.25 j	4.28 c
		N200	18.4 a	59.5 c	0.36 e	4.45 d
		N250	18.8 a	59.0 c	0.44 a	3.98 b
Mean		18.5 a	61.20	0.22	3.98	

Notes: The different lowercase letters in the same treatment such as I or N treatment indicate significant differences ($P < 0.05$) between study seasons. I represents AI and CK irrigation treatments; N represents N fertilizer application rates.

Soil CO₂ emissions in the Spring period were 7.9, 9.8, 10.8, 11.1 and 13.1% higher than those in the Autumn period for the N0, N50, N150, N200 and N250 treatments, respectively (Table 1). During the earlier portion of the growing season, soil CO₂ flux for the AI treatment was

less than for CK. However, as time progressed into the last half of the growing season, CO₂ flux for AI was greater than for CK most of the time (Fig. 3). The cumulative CO₂ emissions from the AI treatment during Spring and Autumn cultivation were 4.43 and 4.0 Mg C ha⁻¹, respectively, which were 54.0 (1.2%) and 43.9 (1.1%) kg ha⁻¹ higher than those observed for the CK treatment ($P > 0.05$) (Table 1). Tomato cultivation during the Spring period increased soil CO₂ emissions under AI by 10.6% compared with Autumn cultivation.

A significant ($P < 0.001$) negative relationship between CO₂ flux and soil moisture was found throughout the experimental period (Fig. 6). However, soil CO₂ flux was strongly and positively correlated with soil temperature, and moderately and positively correlated with soil oxygen content.

3.3. Soil N₂O fluxes

Both positive and negative fluxes of soil N₂O were observed during the Autumn season (Fig. 3d). The uptake of soil N₂O was particularly seen to occur 80 day after transplanting. The peaks of soil N₂O emissions occurred only in the early part of the growing season, and emission rate generally declined with time in the last half of growing season. In contrast to the negative fluxes of soil N₂O observed during the Autumn cultivation, the highest soil N₂O emissions were observed in the Spring cultivation period (Fig. 3c). Higher temperature in Spring cultivation significantly ($P < 0.05$) promoted soil accumulated N₂O emissions by 43.8% compared with Autumn cultivation (Table 1).

Irrespective of other factors, increasing N fertilization rates from 0 to 250 kg N ha⁻¹ resulted in an exponential increase in average soil N₂O emissions from −0.01 to 0.51 Mg CO₂-eq ha⁻¹ (Fig. 4c). At the same

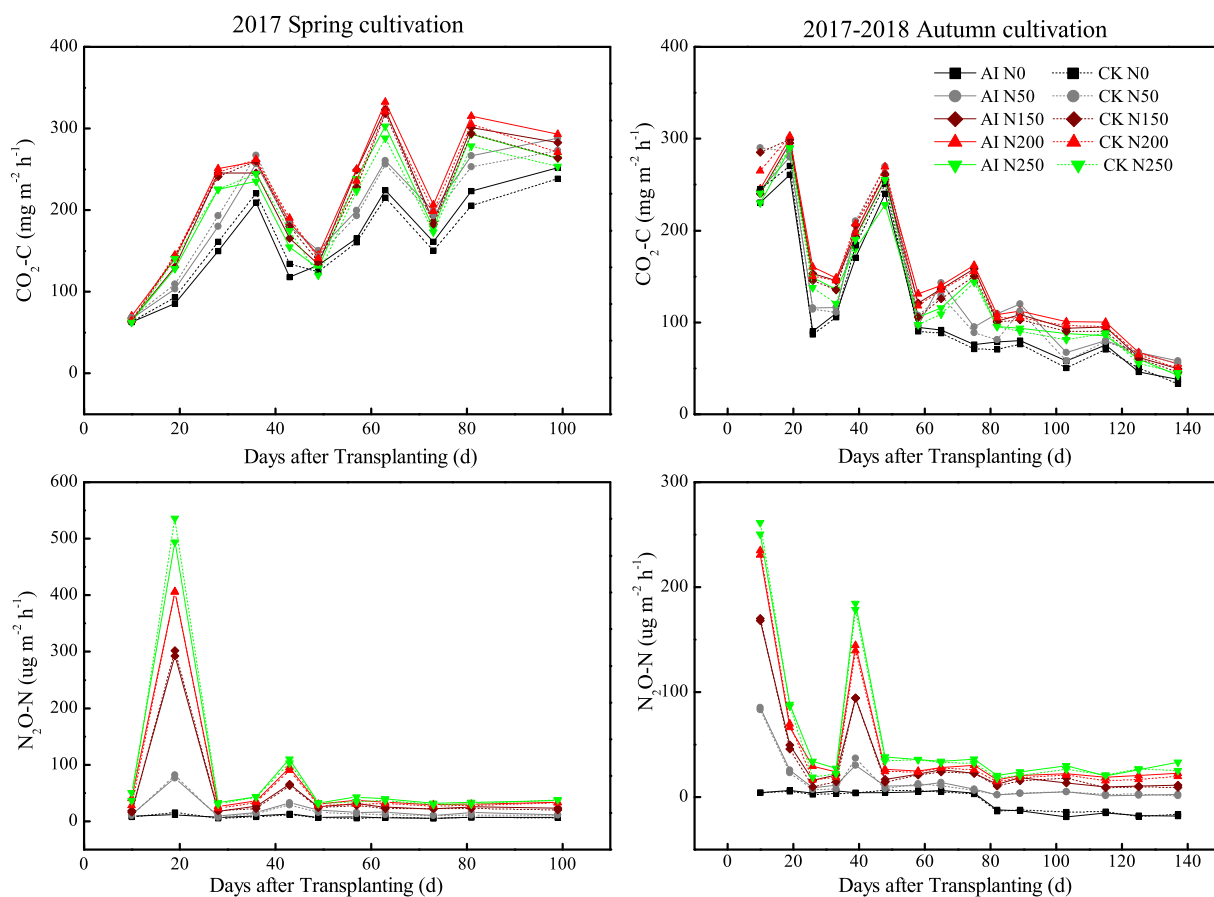


Fig. 3. Seasonal variation of soil N₂O and CO₂ fluxes in the 2017 spring cultivation and 2017–2018 autumn cultivation periods for tomato at Yangling, China. AIN0, AIN50, AIN150, and AIN250 represent the N application rates of 0, 50, 150, and 250 kg N ha⁻¹ under aerated irrigation, respectively. Similarly, the CKN0, CKN50, CKN150, and CKN250 represent the N application rates of 0, 50, 150, and 250 kg N ha⁻¹ under conventional irrigation, respectively.

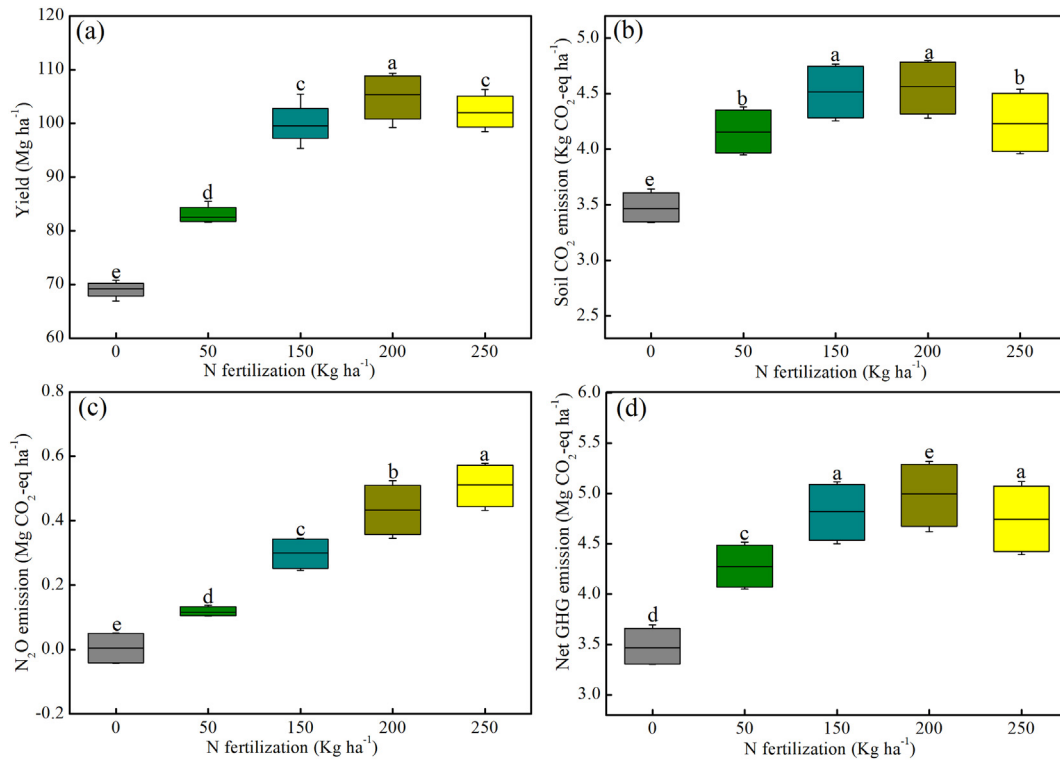


Fig. 4. Effects of nitrogen fertilization rate on average tomato yield (a), soil CO₂ emission (b), N₂O emission (c) and net greenhouse gas emission (GHG) (d) over both Spring and Autumn seasons in both seasons at Yangling, China. Soil CO₂ emission is the soil C loss in terms of CO₂-eq ha⁻¹; positive and negative emissions represent the soil acting as a net source and sink of atmospheric CO₂, respectively. Boxplots show the medians (thick horizontal lines inside the boxes) and the 25th (lower ends of the boxes) and 75th (upper ends of the boxes) percentiles, the whiskers indicated the 5th and 95th percentiles.

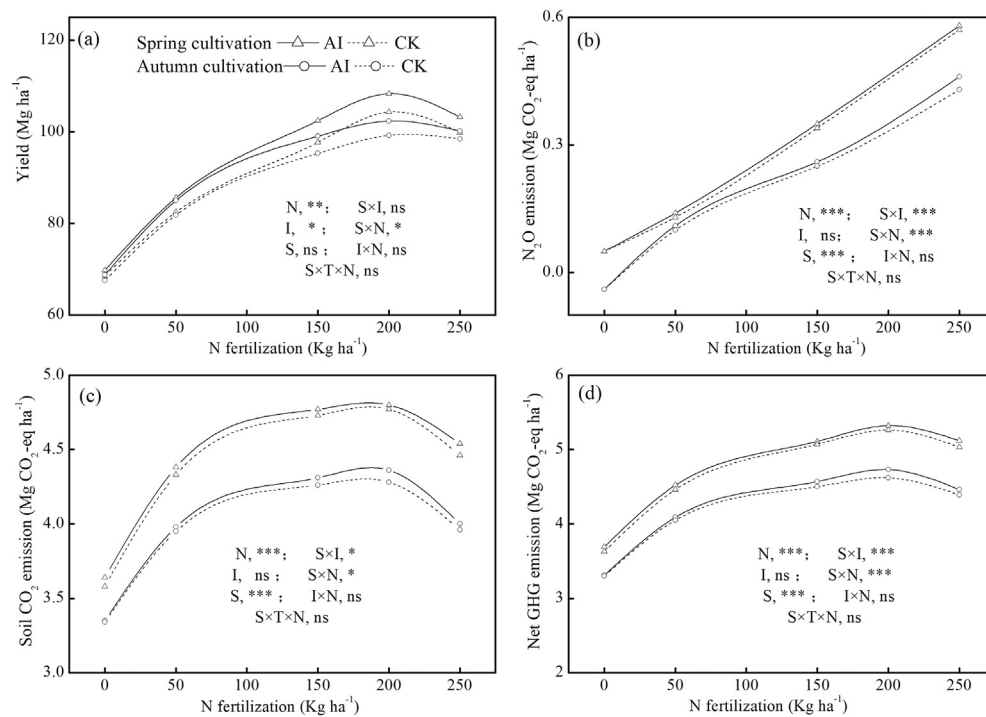


Fig. 5. Response of average tomato yield (a), soil N₂O emission (b), soil CO₂ emission (c), and net greenhouse gas emission (d) to different fertilizer application rates and irrigation practices at Yangling, China. The soil CO₂ emission is the soil C loss in terms of CO₂-eq ha⁻¹; positive and negative soil CO₂ emissions represent the soil acting as a net source and sink of atmospheric CO₂, respectively. AI and CK represent the aerated irrigation and conventional irrigation treatments, respectively. Notes: * and ** signify significant differences between treatments at $P < 0.05$ and $P < 0.01$ levels; ns indicates no significant differences between treatments. I represents AI and CK irrigation treatments; N represents N fertilizer application rates; S represents seasons; S × I represents the interaction between seasons and irrigation treatments; S × N represents the interaction between seasons and N fertilizer application rates; I × N represents the interaction between irrigation treatments and N fertilizer application rates; S × I × N represents the interaction among seasons, irrigation treatments, and N fertilizer application rates.

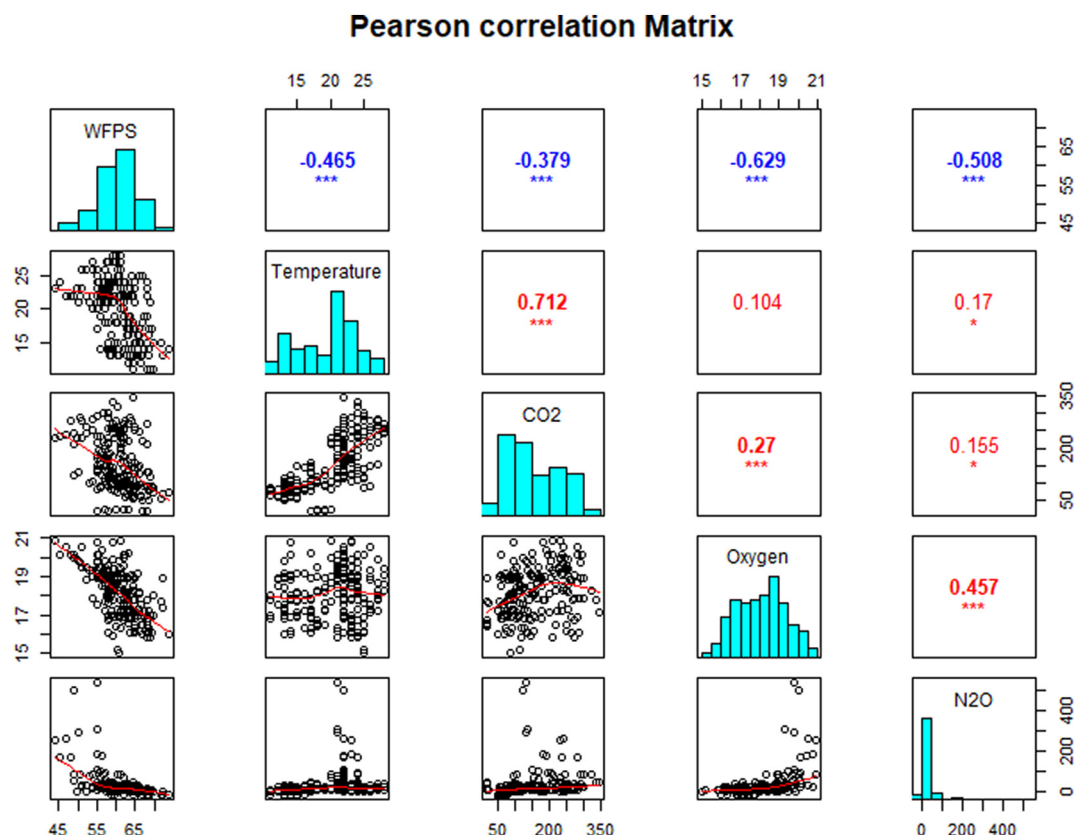


Fig. 6. The Pearson's correlation coefficients between soil CO₂ emissions and N₂O emissions and environmental variables of soil temperature, soil water-filled pore space (WFPS) and soil oxygen content. Notes: The panels with the vertical blue bars (in a diagonal line from upper left to lower right) show the distribution of each variable itself. The lower triangle of panels (below the diagonal line of blue histograms) are the scatter plots of the two correlated variables. The upper triangle of panels (above the diagonal line of blue histograms) gives numbers representing the correlation coefficient between any two variables, and the * and *** represent the significance of the correlation coefficients at $P < 0.05$ and $P < 0.001$ levels, respectively.

N rate, the warmer Spring cultivation period further increased the N effect on soil N₂O emissions by 25.6–42.8% (Table 1). N₂O fluxes from AI soils were generally higher than those from CK (Fig. 3). The mean soil N₂O emissions from AI soils were 0.33 and 0.23 Mg CO₂-eq ha⁻¹ for the Spring and Autumn cultivation periods, and were 3.9% and 5.6% greater than N₂O emissions from CK soils, respectively (Fig. 5; Table 1). The differences were not significant ($P > 0.05$). Spring cultivation increased the effect of AI on soil N₂O emissions by 42.7%. Significantly positive relationships were found between N₂O fluxes and soil temperature and soil oxygen content when considered over the entire cultivation seasons (Fig. 6). In contrast, N₂O fluxes were negatively correlated with soil moisture.

3.4. Yield and net GHG emissions

Fig. 5a shows the response of crop yield to N fertilization under AI and CK treatments in both seasons. The results indicate that the mean yield in the warmer Spring cultivation season was 4.5 Mg ha⁻¹ (5.1%) greater than the mean yield in the Autumn season, but the difference was not statistically significant ($P > 0.05$). However, the yield was significantly affected by the nitrogen fertilization rate and the irrigation management. The highest yield obtained in both seasons occurred with the 200 kg N ha⁻¹ fertilizer rate, and no difference was found between the N150 and N250 treatments. In the Spring cultivation period, the yield of N200 under AI was 53.9%, 27.4%, 3.06% and 2.51% greater than the yield of the N0, N50, N150 and N250 treatments, respectively. The mean yield under AI was 3.4% higher ($P < 0.05$) than with the CK treatment. For the Autumn cultivation period, the yield of the N200 treatment under AI was 49.9%, 26.8%, 4.0% and 3.1% greater than the yields with the N0,

N50, N150 and N250 treatments, respectively. The mean yield under AI was 2.5% greater than with the CK treatment.

The average net GHG emission in the warmer Spring cultivation period was 4.72 Mg ha⁻¹, which was 517.8 kg ha⁻¹ (12.3%) greater than that observed in the cooler Autumn cultivation period ($P < 0.05$) (Fig. 4d). Furthermore, the net GHG emissions showed a similar response to increasing N rates as seen for the soil CO₂ emissions. The effect of a warmer growing season on net GHG emissions became stronger at higher N fertilizer rates. For the N200 and N250 treatments, the net GHG emissions in the warmer Spring cultivation period were 0.61 and 0.65 Mg C ha⁻¹ greater than in the cooler Autumn cultivation period. However, with lower N fertilization rates, the differences between the two seasons were reduced to 0.35, 0.42, and 0.55 Mg C ha⁻¹ in N0, N50, and N150 treatments. In addition, AI resulted in 1.4% greater net GHG emissions compared with CK, but the difference was not significant ($P > 0.05$) between the two treatments.

4. Discussion

4.1. Emissions of soil CO₂

An increase in soil CO₂ emissions in response to warming has been observed in various ecosystems (Zou et al., 2018; Rustad et al., 2001), and this result was confirmed by our present study. A significant positive correlation ($R^2 = 0.72$, $P < 0.001$, Fig. 6) was found between soil temperature and CO₂ emissions. Prevalence of higher temperatures could accelerate decomposition of soil organic C or external sources and lead to C loss to the atmosphere (Lin et al., 2001). Soil mean CO₂ emissions were 10.6% greater during Spring cultivation than during

Autumn cultivation, a result of a 4 °C increase in soil temperature. This emission level was lower than the increase of soil CO₂ emissions (23–40%) in various forest ecosystems (Zou et al., 2018; Rustad and Fernandez, 1998). However, Liu et al. (2015) conducted a warming experiment in a winter wheat-soybean/fallow system and found that warming had no significant effects on soil CO₂ emissions. This showed the specificity of the effect of increasing soil temperature on soil respiration in different crop types and environments and also emphasized the importance of considering impacts of different cultivation seasons in accurately estimating GHG emissions.

Additionally, irrigation and N fertilization, the two main management practices in greenhouse cultivation, also significantly affected soil CO₂ emissions. In the present study, under the same N application rate, the CO₂ emissions of AI were 35.4–58.8 kg ha⁻¹ higher than those of CK ($P > 0.05$). Similar results were also reported by Hou et al. (2016) and Bhattarai et al. (2006). Soil oxygen content was enhanced with the use of AI, which improves the root environment, increasing soil microbial abundance and enzyme activity, and thus increasing soil CO₂ emissions ($R^2 = 0.12$, $P > 0.05$, Fig. 6). Under the same irrigation method, the response of soil CO₂ emissions to increased N application rate generally exhibited an initial increase in emissions followed by a decrease in emissions (Fig. 4b). Two explanations have been offered for this phenomenon. First, N application may mitigate the plant N deficit conditions and promote root growth and aboveground biomass (Kara and Mujdeci, 2010), which would lead to incremental carbon inputs into the soil and stimulation of soil microbial biomass and activity (Campbell et al., 2000; Du et al., 2018b). But excessive N application might cause soil acidification and decrease soil microbial activity (Zhong et al., 2015; Wei et al., 2018; Compton et al., 2004). Second, appropriate N addition increased soil microbial abundance and enzyme activity and might stimulate soil organic matter mineralization (Du et al., 2018b; Lu et al., 2011). In general, the soil CO₂ emissions in greenhouse cultivation were promoted by AI and N application, especially under Spring cultivation.

4.2. Emissions of soil N₂O

In the present study, soil N₂O fluxes switched between net uptakes and net emissions during the study period (Fig. 3). This trend was strongly regulated by irrigation and N fertilizer application. Soil N₂O emissions increased with increasing N application rate. The lowest soil N₂O emissions were always found for the no N application treatment, and negative values of N₂O were observed during the late growing season. This might be because N deficiency without N application inhibits crop growth and reduces water consumption, resulting in a higher soil moisture content (Gu et al., 2017; Fig. 2d and i), which, along with low NO₃⁻ availability, induces denitrification in the surface soil layers due to the reduced NO₂⁻ availability for denitrifiers (Jungkunst and Fiedler, 2007), and converts atmospheric N₂O into N₂ (Hou et al., 2016; Yu et al., 2000); increasing the soil oxygen content would increase soil N₂O emissions. In the present study, the soil N₂O emissions in the AI treatment were 3.9–5.6% higher than those in CK, but the differences were not significant ($P > 0.05$, Fig. 3). In addition, under the same treatment, increasing soil temperature in Spring cultivation further promoted soil N₂O emissions by 43.8%, especially when soil had higher water and fertilizer input (Fig. 5). In contrast to this, Trnka et al. (2013) and Xu et al. (2016) reported that warmer and drier conditions potentially slow down the decomposition of soil organic carbon and alter soil nitrifier and denitrifier communities, resulting in a decrease in soil CO₂ and N₂O emissions. However, irrigation was the only water input for crop growth because precipitation was prevented by the polyethylene sheet covering the greenhouse. Thus, in order to decrease the soil GHG emissions in the greenhouse, reducing the amount of N application might be a viable option.

4.3. Yield and net GHG emissions

The three factors considered in this study (irrigation, N fertilizer, and growing seasons) not only altered soil GHG emissions, but also affected crop yield formation by changing soil water, fertility, gas, and heat conditions (Wang et al., 2018). In the present study, the maximum tomato yield was obtained at N200 treatment. Furthermore, the yield of AI along with N200 was about 3.5% higher than for CK treatment. This was consistent with our recent study where reduced N application under AI promoted plant N uptake and yield increases (Du et al., 2018b). Although the yield in Spring cultivation was 5.1% ($P > 0.05$) higher than in Autumn cultivation, the net GHG emissions were increased by 12.3% (517.8 kg ha⁻¹) ($P < 0.05$). Thus, for crops that can be cultivated several times a year in greenhouse systems, choosing the cooler season as often as possible would avoid or minimize the adverse effects of a warmer environment. From the results of the present study, we recommend tomato production during the Autumn cultivation period in conjunction with AI and an N fertilizer application rate of 200 kg ha⁻¹.

Facing the projected continued increase in global temperature, there remains, however, a very important agricultural production issue: how to effectively control or reduce net GHG emissions under future warming conditions (IPCC, 2007; Bradford et al., 2016). Thus, putting forward effective management practices to ensure farmers' economic returns while reducing GHG emissions is necessary. In the current study, when the N application rate was reduced from 250 to 200, 150, 50, and 0 kg N ha⁻¹, the corresponding incremental differences in net GHG emissions between the Spring cultivation and the Autumn cultivation periods declined from 0.65 to 0.61, 0.55, 0.42, and 0.35 Mg CO₂-eq ha⁻¹ (Ju et al., 2009; Tian et al., 2012) (Fig. 5). The mean tomato yields for the N200 and N250 treatments were 1.9% and 4.0% higher than N150, but the net GHG emissions were very high. When the N application rate was reduced to 150 kg ha⁻¹ under AI, the net GHG emissions were significantly reduced, and the yield was 3.7% higher than under CK. Thus, use of AI and a fertilizer rate of 150 kg ha⁻¹ for tomato production in a warmer cultivation period, i.e. Spring cultivation, can significantly reduce net GHG emissions while maintaining crop yield.

5. Conclusions

The results of our greenhouse cultivation clearly indicate the existence of complex interactions among growing seasons, irrigation method, and N application. AI along with N application significantly increased crop yield, but also increased GHG emissions. Compared with Autumn cultivation, Spring cultivation further increased tomato yield, soil CO₂ and N₂O emissions by 5.1% ($P > 0.05$), 10.6% ($P < 0.05$), and 43.8% ($P < 0.05$). In order to maintain crop yield while reducing GHG emissions, AI along with 200 kg ha⁻¹ in Autumn cultivation was recommended for local farmers. To cope with a future warming climate, exemplified in this study by Spring cultivation, AI along with 150 kg ha⁻¹ could be recommended.

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